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Geotechnical Data Base for the City of Zagreb and its Application in Site Response Analyses

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GEOTECHNICAL DATA BASE FOR THE CITY OF ZAGREB AND ITS APPLICATION IN SITE RESPONSE ANALYSES

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ABSTRACT

Geotechnical reports, filed in the city archives, are the source of data among which relevant properties for mechanical soil behaviour and site response analyses are recognized and digitised. The properties are digitised in an organized manner into the GIS related software called "Techbase", developed by "MINEsoft", Lakewood, Colorado. The basic element of the database is a boring log containing distributions of soil properties with depth. More than 150 boring logs, located in the western part of Zagreb, are digitised and their coordinates mapped using "Techbase". The aim of this paper is not only to describe the collection of the geotechnical database, but also to present its use for developing techniques for the estimation of soil-related response to earthquakes as well. The process of obtaining the seismic design model and its use in assessing free field ground acceleration are described. As borings usually do not reach deeper than ten meters, the influence of upper ten meters on amplification of maximum ground acceleration is pointed out.

INTRODUCTION

Geotechnical information and how to present it

According to Eurocode No. 7 (Geotechnics), the presentation of geotechnical information should include a factual account of all field and laboratory work and a documentation of the methods used to carry out the field investigations and the laboratory testing. A geotechnical report should include, among other things, a compilation of boring logs with a description of subsurface explorations, tabulation of quantities of field and laboratory work, dates between which field and laboratory works were performed, evidence of ground water and fluctuations of groundwater table in the boreholes during performance of the field work and in piezometers after the completion of the field work. Geotechnical information should be evaluated by an experienced geotechnical engineer. This paper deals with geotechnical information which, when once collected and verified according to Eurocode recommendations, is made in a form of a database managing system.

Benefits of preparing a geotechnical managing system

Benefits of preparing a geotechnical managing system were widely reported and discussed in papers by Abramson and Lee (1996), McGinnity and Russell (1996), Nathanail and Rosenbaum (1996), Nicholls et al. (1996), Oliver and Toll (1996) and Threadgold (1996) at International Conference: "Advances in site investigation practice", held in London in 1995. In this paper only some of them are mentioned. An ultimate goal of database managing systems is to establish a flow of electronic data from geotechnical investigators to a data consumer. If the database is made in systematic and comprehensive manner it serves as a source of data for various users. Site investigation specialists use it as a tool for a quick preparation of a geotechnical report. A designer and a consultant may, by filtering and querying, determine whether the parameters from the database have significance or whether they are mutually related. By doing this they ease the effort to allow modelling of ground conditions and selection of design parameters. A client will use a database for storing large quantities of data and for future reference.

Due to the fact that most geotechnical information is compiled in boring logs, an effective electronic data managing system of boring logs comes out as a powerful tool to a geotechnical engineer. The data managing system provides a ready access to in situ measurements and laboratory testing results, which makes a geotechnician possible to quickly assess local geotechnical conditions. The system also helps geotechnical engineers in gaining experience in soil conditions in the particular area; a systematically organized database of boring logs from a nearby field locations will help with planning the type and the number of new soil explorations and locations of borings for the purpose of building in much populated areas such as cities. The next step may be the use of the database for the research purposes. After systematic analyses and mapping of geotechnical data on the particular region, on the basis of the local geologic conditions and other relevant parameters, geotechnical engineer can evaluate and forecast the behaviour of local soil and structures during earthquakes.

PREPARATORY WORK FOR GEOTECHNICAL DATABASE FOR THE CITY OF ZAGREB

Preparatory work, a working team, a consultant and software

In 1995 the city authorities of Zagreb started to fund a research project aimed at the development of a computer-based geotechnical database for the city of Zagreb. The first step was the creation of a computerised relational database for the storage and manipulation of both the past and future site investigations. If the project proves successful, the next step will involve the use the database for the evaluation of the behaviour of local soil during earthquakes, and finally, for seismic microzonation. As mentioned above, the source of geotechnical data were boring logs containing the distributions of various soil properties. For collecting boring logs from the Zagreb area and organising them to a database a working team was founded. The team started working in September 1995 by collecting geotechnical reports for database and by preparing software for data manipulating and presentation.

A consultant of the team is Prof. Mladen Vucetic who has already been working on the similar research project (Vucetic et al., 1994). His principle is to make GIS with layers of maps with geotechnical and other data relevant for seismic studies, such as topography, ground water table elevation, earthquake faults, road network, lifelines, strong ground motions and damage distributions of past earthquakes, etc. Each data layer can be digitised and transformed into a computer generated map. Ultimately, the data in the geotechnical database and these maps will be manipulated and compared in various ways in order to identify the patterns of the local geotechnical and geologic effects on the surface motion and damage.

It is planned that the same research for the Zagreb area is made. Due to the fact that the geographic location of a boring log is a key parameter for making out a consistent managing system, it was decided that GIS - type software should be used for managing the database. With the courtesy of "MINEsoft" Lakewood, Colorado the team was provided with geotechnicaly oriented GIS - software named "Techbase". It was expected that final product would be a GIS - suitable database for the evaluation of preliminary geotechnical properties of the Zagreb area and the base for the research purpose such as soil-related earthquake effects.

Choice of soil properties for the database

Written reports of boring logs, in situ investigation and laboratory measurements are usually compiled in geotechnical reports. In the city of Zagreb, most geotechical reports are filed in the archives, which is installed in the city townhall (the city of Zagreb files). Before starting the digitisation of boring logs from geotechnical reports to database, some preparatory work had to be done. First of all, a consistent system of hole identifications for locations and sample numbering was established. As a pilot-project the data from approximately 150 geotechnical boring logs were incorporated into a "Techbase" along with a computer map of the western part of the Zagreb area.

Detailed boring data were prepared for each boring log location, which made the database three-dimensional. The data from laboratory tests encompass: soil classification properties (density, mass density, Atterberg limits, natural water content and grain size distribution), shear strength parameters and classification symbol with a short description of material properties. In the Republic of Croatia, Unified Soil Classification System (USCS), founded by Prof. A. Casagrande and modified at Massachusetts Institute of Technology is widely accepted. The system is based upon the grain size distribution and Atterberg limits. The data from in situ tests encompass the standard penetration test (SPT) results and, what is of particular importance for seismic analyses - shear wave velocities. Shear wave velocities are used for calculating shear moduli, basic parameters of seismic design profile (see Section 3).

A shear wave velocity is a result of measurement by geophysical method, which is not routinely carried out with other standard in situ investigations. Therefore, shear wave velocities are not usually provided in ordinary geotechnical reports. Even when there are some shear wave velocity data, user should take into consideration the type of the test with which they were obtained. Shear wave velocity can be measured in the field using geophysical methods such as down-hole and cross-hole velocity testing or by using surface wave measurements such as seismic refraction. Recently, yet another method for measurement of shear wave velocity was introduced; due to the fast development of computer technology, shear wave velocities are obtained from the spectral-analysis-of-surface-waves, SASW (for details turn to, for example, Gucunski, 1991). Every method has its benefits and drawbacks. Therefore, before digitised, the shear wave velocity data should be evaluated critically. Cross-hole and down-hole measurements are generally considered more reliable then other methods of measuring shear wave velocities.

Besides shear wave velocities v_s, mass densities of a soil ρ are important for earthquake engineering studies. They are related to maximum shear modulus at very small strains G_{max} by the equation:

$$G_{max} = \rho \, v_s^2 \, . \qquad (1)$$

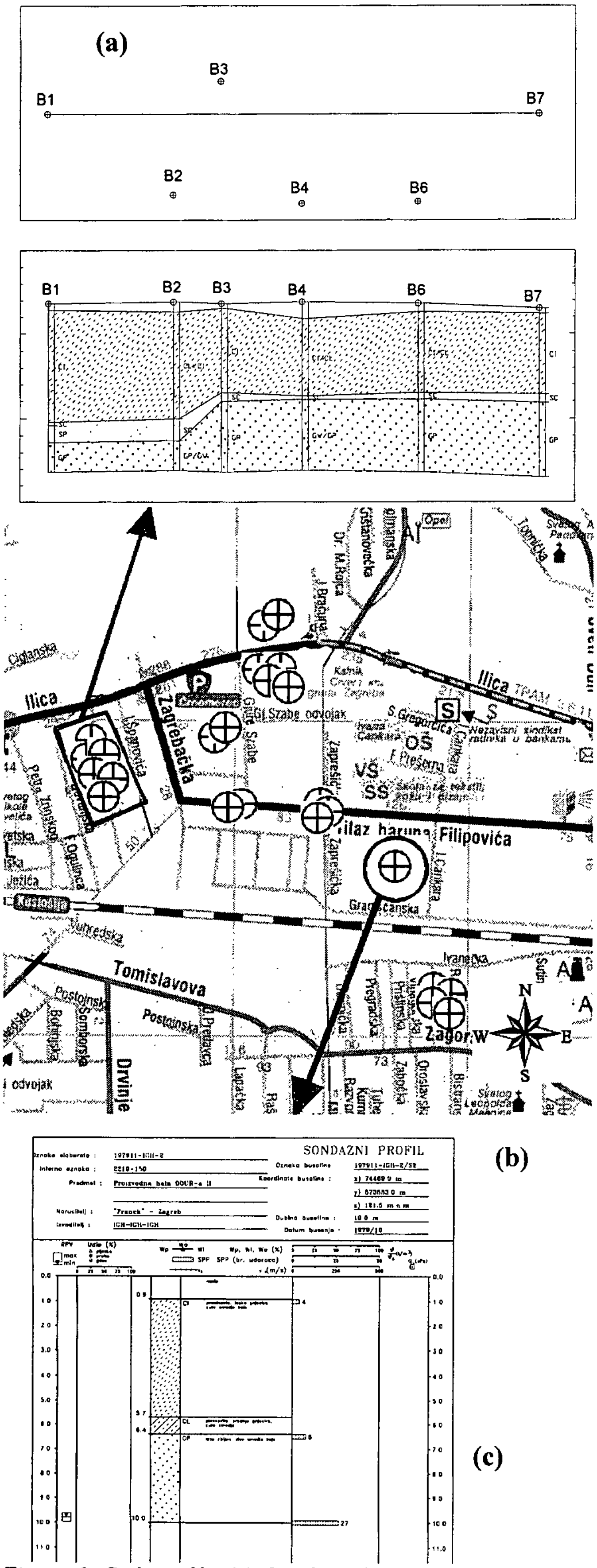

Figure 1. Soil profile (a) for the selected boreholes on the digitised map (b), and selected boring log (c)

As an alternative to laboratory or field measurement of soil properties, dynamic moduli and damping for soils may be estimated as a function of a soil type based upon recommendations for typical values from previous investigations. Should the shear wave velocity data be not available, another parameter, namely the blow count from SPT can be used. There are various correlations between SPT blow count and other geotechnical properties such as some correlations between SPT and v_s for specific soil types. Some of them are defined by Imai and Tonouchi (1982):

$$G_{max} = c\ (N)^a\ . \qquad (2)$$

where N is in blows per foot of penetration and c and a are coefficients. Due to uncertainty involved in using these types of empirical correlations, considerable judgement is required in interpreting results. Sensitivity studies on the values of these parameters are recommended.

Another important parameter is a plasticity index of a soil (PI), which can be correlated with some of the most important dynamic soil properties (Dobry and Vucetic, 1987). PI may be easily calculated from Atterberg limits, which are usually provided in standard geotechnical reports.

The collection, organization, critical evaluation and subsequent digitisation of the boring log data in a uniform and meaningful manner represented the primary activities of the project. Data, which were captured from geotechnical reports, were imputed into a computer manually. Most of manual work was done by the undergraduate student Eduard Ćoza as a part of his diploma thesis, which he has finished successfully in February 1996. The work on this project was presented by Kvasnička et al. (1996).

The boring log format, for the borehole selected on the digitised map, with the classification and description of soils and other geotechnical data specifically devised for this project is shown in Fig. 1(c).

<u>Preliminary manipulations of boring log data</u>

As for the boring log location, the principle was to have coordinates of every boring log location digitised and mapped. For the two selected points on a digitised map, the capability of "Techabase" is to automatically plot "cross-section" between points over selected width. Additional software was implemented to "Techbase" to obtain the so-called "soil profile" in which program automatically connects layers with the same elementary soil type (gravel, sand, silt or clay). An example of soil profile is presented in Fig. 1(a). Another possibility of "Techbase" is microzonation, i.e. contouring zones with data between specified limits. Due to fact that in our pilot-project only limited, rarely distributed boring logs were input, there is a little effect of making zones.

SITE RESPONSE ANALYSES

Evaluation of the effects of local soil conditions on surface acceleration

The formation of seismic zones would be of primary interest for the research project. These zones could not be attained by simply averaging some data from boring logs, but also by caring out analysis procedure for finding out zones with the same characteristic seismic parameter such as a peak surface acceleration in the free field. This acceleration is used in evaluation of the seismic response of structures and subgrade liquefaction potential. The peak ground surface acceleration, along with other relevant data, is dependent on the soil stratification. To calculate its value usually simple analysis procedures, that are within the technical capability of the general technical community, are used. The simplified analysis described here presents one way in which peak surface acceleration, by taking the influence of local soil condition, may be assessed.

Propagation of seismic waves through local soil is modelled as horizontal shear waves (SH) propagating vertically upwards through horizontal soil layers. This is called "a seismic design model" in which the simplification consists of in not accounting for the influence of vertical motions, compression waves and usually lateral non-uniform soil conditions. The fact that only horizontal component of the soil motion is taken into consideration is in compliance with common design practice for geotechnical engineering in assessing, for example, seismic stability and liquefaction potential. Considering the fact that the main free field characteristics as well as the results from the field and laboratory studies meet all the requirements of the considered analysis, the selection of this dynamic analysis method is completely justified.

In the seismic design model, horizontally layered soil column is treated as a linear visco-elastic material characterized by an elastic modulus and viscous damping ratio. Non-linear strain dependent behaviour of soil is accounted for by calculating with "equivalent linear modulus and damping" which are obtained from laboratory measurements under uniform cyclic loading. An equivalent linear modulus and damping must correspond to representative shear strain which is taken as 65 percent of the maximum shear strain calculated in the site response analysis. Because the maximum shear strain is not known in advance, a numerical procedure must be performed in an iterative manner. An equivalent linear analysis is typically performed in the frequency domain, employing the principal of superposition to calculate the time history of ground motions.

Dynamic soil parameters for the seismic design model are: the shear modulus for each layer (or shear wave velocity and mass density), fraction of critical damping for each soil type and curves relating modulus reduction and damping curves to shear strain (necessary for the iteration procedure). In the model, horizontal soil layers are underlied by the bedrock, which is defined as a rock or soil with shear wave velocity greater then 700 m/s.

Seismic influence is represented by an acceleration-time history, which may be input as the motion at a hypothetical bedrock outcrop or at the bedrock-soil interface at the base of a soil column. Generally, the results of analysis provide shear stress- and acceleration-time histories for each layer within the soil profile. For the purpose of seismic zoning relevant is only maximum acceleration on the surface of the model, which may be provided by the same procedure.

As may be seen, evaluation of local soil condition may be obtained by using soil data from the boring logs for input soil parameters along with other relevant data controlling effects of earthquakes such as peak horizontal acceleration in lithified earth material and site dependent accelerogram as well. The structural analyses typically require information on the spectral content of ground motions, which means a complete time history to characterize the design motion. Behaviour of characteristic building may be modelled as one degree of freedom system (SDOF).

An example with SHAKE

Even with a limited number of boring log data in the database an attempt was made to model, for a selected part of the Zagreb area, the influence of local soil on earthquake effects. For the seismic analysis the computer program SHAKE was used, originally developed by Seed and his co-workers (Schnabel et al., 1972). SHAKE is perhaps the most commonly used computer program for one-dimensional equivalent linear seismic site response analysis. Soil properties include the maximum shear modulus or shear wave velocity and mass density for each soil layer plus curves relating the reduction in modulus and damping ratio to shear strain for each soil type. Maximum dynamic shear moduli are applied for deformations up to $\gamma = 10^{-4}\%$ while, for nonlinear range of deformations, from $\gamma = 10^{-4}\%$ to 10%, the relationships between the dynamic shear moduli and damping and shear deformations, defined based on laboratory tests, have been applied.

For the seismic site response analysis selected was the western part of Zagreb area. The soil is of sediment origin and therefore horizontally layered. To find the representative values of maximum shear modulus, shear wave velocity and mass density for every soil layer should be found. Mass density of soils is usually included in boring log data, but, for want of shear wave velocity data, and because of the fact that SPT tests are usually carried out for geotechnical reports, SPT-shear wave velocity correlations were used. For the calculation purpose soil was subdivided to horizontal layers: two surface layers of thickness 1.0 m, and deeper layers of 2.0 m. With the statistical tool, which is a part of "Techbase" software, average values of SPT and mass density were calculated.

Mass density and SPT data from boring logs are originally imputed in separated, the so called, flat-type tables in

"Techbase". The flat-type tables are common types of tables, similar to a spreadsheet format where rows equal records and columns equal fields. For the purpose of finding representative values of SPT in the "Techbase", a virtual join-type table was formed. The join-type table does not exist as a "physical storage" but provides a logical link between two flat tables, which are joined by a common "key". Through the join-type table filters were used to create working database with average values of SPT and a mass density. The next important parameter is a type of soil. It is on soil that the curves relating to the reduction in modulus and damping ratio to shear strain and SPT-shear wave velocity correlation are dependent on. The type of soil in a layer is marked with the USCS classification symbol. The variety of classification symbols was found for each soil layer as a consequence of judgement of the personnel who were identifying the soil specimens in situ.

Therefore, only the symbols of principal soil groups: C (clay), M (silt), S (sand) and G (gravel), instead of CL (low plasticity clay) or GW (well graded gravel), for instance, were chosen for symbolizing the material type. For example, in the area bounded with angular spherical coordinates (Gauss - Krüger coordinate system): X = 74536 and 74955 (latitude), Y = 573468 and 573685 (longitude), the wide scatter in results was found (Table 1.)

The trouble with deriving a seismic design model according to boring logs is that boring logs do not usually reach depths greater then 10.0 to 15.0 meters. But, as discussed below, most change in seismic motion usually happens in the surface layers thus making them more important than the layers below.

Soil characteristics for greater depths were extrapolated on the basis of data from hydrothermal borings (bored by a National Oil Company - INA) that were bored up to lime rock at a depth of 2000 m below the soil surface. Another source was the paper by Jurak and Mihalić (1995) for the Zagreb area, the paper by Hernitz et al. (1981) and geotechnical reports for the nearby site at Prevlaka (in 1984) where numerous field and laboratory investigations of Quaternary deposits have been performed. The investigations were undertaken in order to obtain geotechnical and geological basis for design and construction of a nuclear power plant. Part of the non-destructive investigations included geophysical investigations composed of geoelectrical explorations as well as shallow seismic reflection and refraction measurements, gravity and magnetic survey and deep reflection seismic measurements.

Within the investigation area 6 boreholes were drilled to the depth between 251 and 425 m. The drill cores from all the boreholes, composed of the disturbed and undisturbed samples for geomechanical investigations, were collected within the uppermost hundred meters.

The deposits belong to the Lower, Middle and Upper Pleistocene with Holocene. The deposits of the Lower Pleistocene lie below the arbitrary marker 'Q' but the boundary with Upper Pliocene could not be determined with any certainty. From the lithologic point of view, clays and silty clays are predominant (towards) the deposits with fine- to medium-grained sands. Immediately below the marker 'Q' lies a rather remarkable clayey layer. The layers are almost horizontal, the dips are approximately 1°, and the greatest dips do not exceed 5°. Data for the seismic design model are presented in Table 2. Shear wave velocities for smaller depths were calculated on the basis of SPT blow counts according to Imai and Tonouchi (1982).

Table 1. Statistics of the SPT and mass density results.

depth [m]	0 - 1.0	1.0 - 2.0	2.0 - 4.0	4.0 - 6.0	6.0 - 8.0	8.0 - 10.0	10.0 - 12.0
SPT_{av}	-	6	7	8	8	11	12
ρ_{av} [t/m^3]	-	1.88	1.9	1.86	2	-	-
n_C	14	23	33	17	19	10	2
n_G	0	0	4	1	0	0	0
n_S	0	0	0	0	5	5	2
n_{h+f}	19	2	0	0	0	0	0

SPT_{av} - average number of occurrences of a blow counts per foot in the interval,
ρ_{av} - average value of mass density of soil in the interval,
n_C - number of occurrences of *C* soil classification symbol in the interval,
n_G - number of occurrences of *G* soil classification symbol in the interval,
n_S - number of occurrences of *S* soil classification symbol in the interval,
n_{h+f} - number of occurrences of *humus* or *fill* in the interval.

In the model, it is accepted that the layers spread horizontally on a large distance, which is characteristic for the site being investigated. The vertical layer proportions were divided, primarily, by the natural border lines of the different soil layers, and then each separate layer is divided into sublayers in order to include the change in some parameters with the profile depth. Horizontal soil layers are underlied by the bedrock, which is defined as a rock or soil with shear wave velocity greater then 700 m/s. We assume a position of the bedrock in our model at a depth of 50.0 m. A complete seismic design model is presented in Fig. 2.

Table 2. Data for the seismic design model.

layer depth [m]	material description	density [t/m^3]	SPT	correlation	shear wave velocity [m/s]
0.0-4.0	humus and clay, lenses of sand and gravel	1.92	7	$v_s=63.6*N^{0.453}$	154
4.0-6.0	clay with thin layers of sand and gravel	1.89	7	$v_s=63.6*N^{0.453}$	154
6.0-8.0	clay with thin layers of sand and gravel	1.93	12	$v_s=63.6*N^{0.453}$	196
8.0-10.0	clay with gravel layer	2	15	$v_s=63.6*N^{0.453}$	217
10.0-13.0	gravel and sand mixtures	2*	no data	-	580*
13.0-50.0	sandy clay	2.05*	no data	-	650*

* values obtained from hydrothermal boreholes.

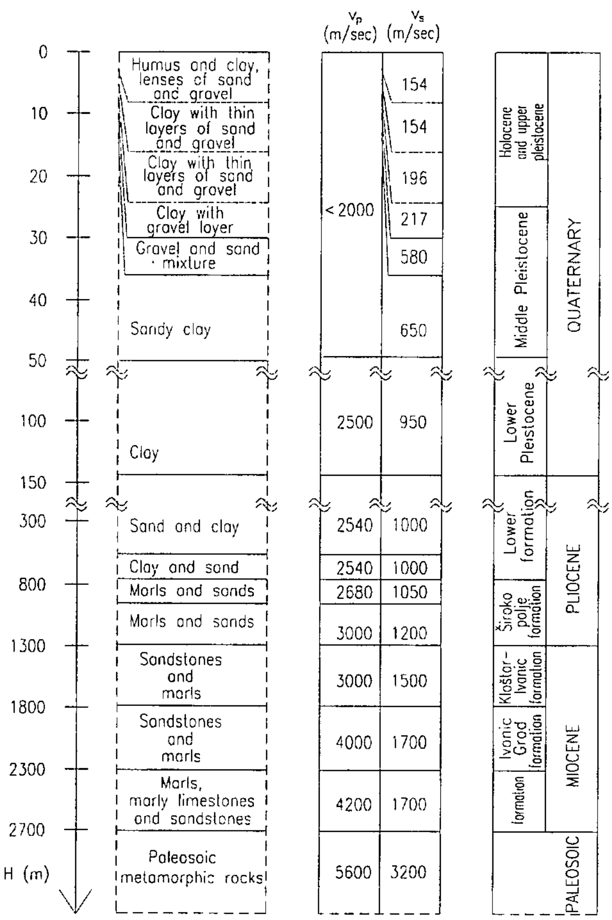

Figure 2. Seismic design model.

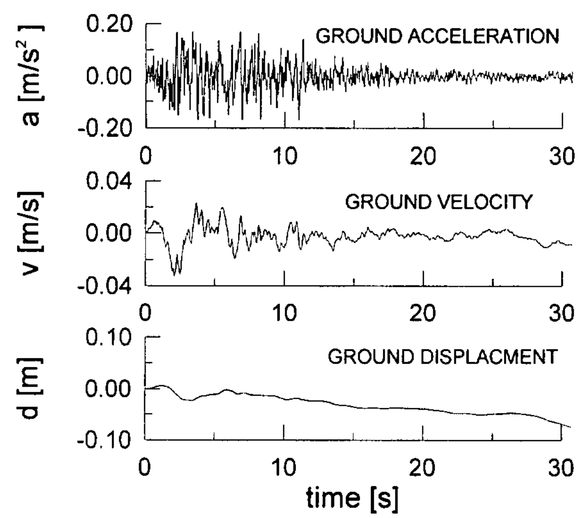

Figure 3. Ground acceleration, velocity and displacement history, compatible with the response spectrum from US NRC R.G. 1.60.

Results of dynamic soil response analysis

Dynamic response of soil was determined by free field dynamic analysis, defining the dynamic response of the layers up to the depth of 50 m. Seismic influence is represented by an acceleration-time history which was input as the motion at a hypothetical bedrock outcrop. It was acceleration-time history compatible with the response spectrum from US NRC R.G. 1.60. (Fig. 3.). This was a strong earthquake, with a favorable frequency content, which means that it includes a wide range of frequencies, which are of interest for the analysis of the model and for the definition of the dynamic response of the system for different resonant conditions.

The selected ground acceleration-time histories were normalized with respect to maximum accelerations and were defined as dynamic excitation of outcropping layer with average soil conditions. The dynamic analyses were carried out for a maximum input acceleration of 0.118 g and 0.198 g that correspond to return periods of 100 years and 1000 years respectively (Stanić and Cvijanović, 1987).

By the dynamic response of the seismic design model, the maximum ground accelerations were determined along the whole depth of the model. These values were determined on the contact surfaces of different soil layers and on the site surface. The maximum accelerations on the site surface are 0.237 g and 0.420 g for return periods of 100 and 1000 years respectively. The graphic presentations of the change of the maximum acceleration along the profile depth for two maximum acceleration levels are presented in Fig. 4.

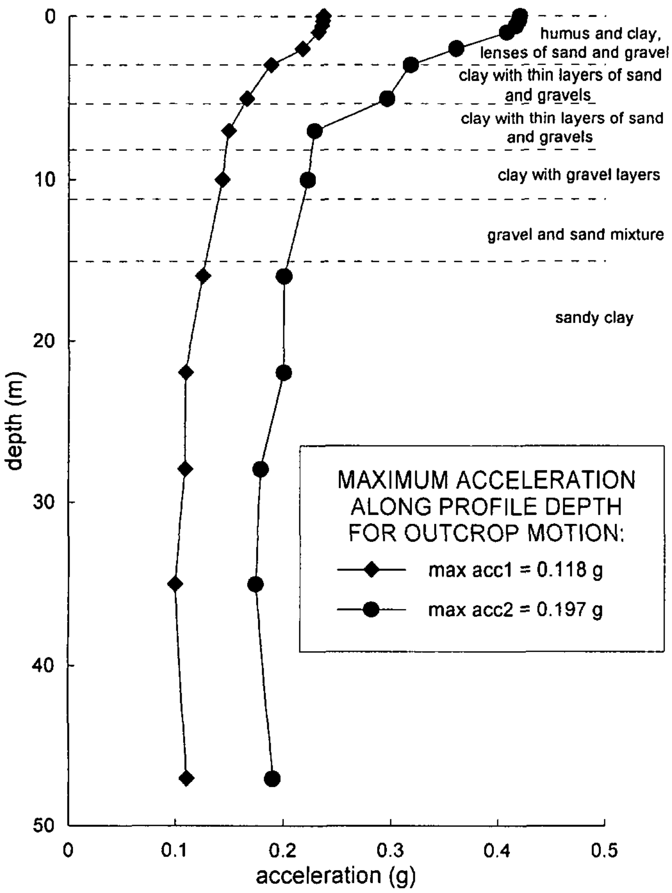

Figure 4. The graphic presentation of the change of the maximum acceleration along the profile depth for two maximum acceleration levels.

The maximum acceleration change for both input accelerations along the depth of the profile has the same tendency, showing sudden amplification in upper eight meters, which is in compliance with the recorded data measured in many locations under similar geological conditions in the world (see, for example, Oka et al. 1996).

CONCLUSION

This paper deals with the development of the geotechnical database managing system for the city of Zagreb and its application in site response analyses. The source of data is geotechnical reports filed in the city archives. A consistent syntax for key field values is provided. The basic element of the database is a boring log containing distributions of soil properties with depth. More than 150 boring logs located on the western part of Zagreb are digitised and their coordinates mapped using "Techbase".

The aim of this paper is not only the collection of the geotechnical database, but its use for developing techniques for the estimation of soil-related response to earthquakes as well. Described is the process for obtaining a seismic design model and its use in assessing free field ground acceleration. While developing the seismic design model, if shear wave velocity data (v_s) are not available, the blow count from the standard penetration test (SPT) can be a help. Various correlations between SPT blow count and v_s for specific soil types were showed. A wide scatter of SPT results may be attributed to the various parameters that can influence the results, including the type of equipment with which it is carried out. Some of these parameters could not be properly controlled during the test. Therefore, this kind of data should be evaluated by an experienced engineer. For future subsurface explorations, direct measurements of shear wave velocities would be highly recommended.

As standard geotechnical borings usually do not reach deeper than ten meters, the attention is drawn to the influence of upper ten meters on the amplification of maximum ground acceleration. On calculating the maximum ground acceleration, the main change in the foreseen maximum accelerations is observed exactly in upper layers and the design of seismic microzoning on the basis of boring logs is therefore justified.

To improve the knowledge of the patterns of the local geotechnical and geologic effects on the ground surface motion and damage, the next step will involve the comparison and manipulation of data from boring log database with other earthquake-relevant layers of maps such as topography, ground water table elevation, earthquake faults, road network, lifelines, strong ground motions and damage distributions of past earthquakes, etc.

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